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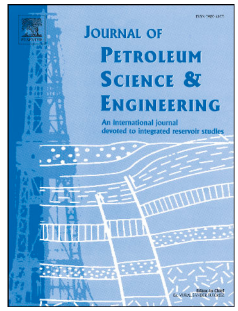

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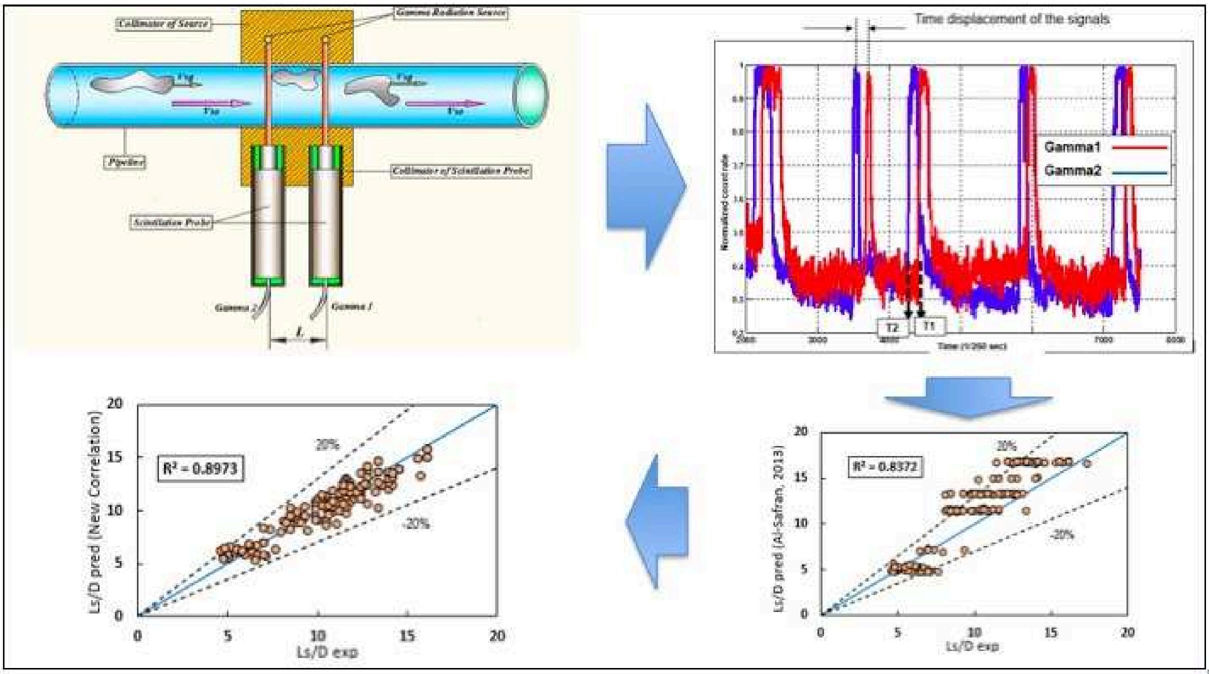
Collimator of Source
Gamma Radiation Source
Pipeline
Collimator of Scintillation Probe
Scintillation Probe
Gamma 2
Gamma 1
L
Time displacement of the signals
Gamma1
Gamma2
T2
T1
Ls/D pred (New Correlation)
Ls/D exp
R² = 0.8973
20%
-20%
Ls/D pred (Al-Safran, 2013)
R² = 0.8372

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Slug length for high viscosity oil-gas flow in horizontal pipes: experiments and prediction

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Abstract

An experimental investigation was carried out on the effects of high liquid viscosities on slug length in a 0.0762-m ID horizontal pipe using air-water and air-oil systems with nominal viscosities ranging from 1.0-5.5 Pa.s. The measurements of slug length were carried out using two fast sampling gamma densitometers with a sampling frequency of 250 Hz. The results obtained show that liquid viscosity has a significant effect on slug length. An assessment of existing prediction models and correlations in the literature was carried out and statistical analysis against the present data revealed some discrepancies, which can be attributed to fluid properties in particular, low viscous oil data used in their derivation Hence, a new high viscous oil data presented here from which we derive a new slug length correlation was derived using dimensional analysis. The proposed correlation will improve prediction of slug length as well as provide a closure relationship for use in flow simulations involving heavy oil. This is important since most current fields produce highly viscous oil with some reaching 10 Pa.s.

Keywords: High viscosity oil, gamma densitometer, slug length, translational velocity, two phase flow.

1 Introduction

1.1 Background

The simultaneous flow of gas and liquid in pipelines occurs in many industrial applications which includes the production and transportation of oil and gas from wells. Slug flow is acknowledged as one of the most commonly observed flow patterns for horizontal and near horizontal pipes in operation. This flow pattern is characterized by the intermittent flow of liquid slugs through the whole cross-sectional area of the pipe separated by elongated gas bubbles. A combination of the liquid slugs and the elongated gas bubbles form what is called a slug unit schematically shown in Fig.1. On account of their practical relevance, intermittent flows have lately been investigated both theoretically and experimentally with more emphasis laid on conventional resources (i.e. air-light oil and air-water systems).

With the rapid depletion of conventional oil reserves (i.e. those of low to medium viscosity) due to increased energy demands, heavy oil has become a major constituent of unconventional fossil fuel resources. Other unconventional oil sources are tar sands, bitumen, tight gas, coalbed methane (CBM), shale gas, and methane hydrates and together, they constitute a major part of overall global oil resources as illustrated in Figure 2. Conventional crude oil accounts for only 22% of current known reserves. Therefore, it is of utmost importance to study the behaviour and characteristics of highly viscous oils especially their multiphase flow characteristics since they are produced along with water, gas, and other production fluids.

Figure 1: Slug Flow Geometry (Baba, 2016)

Figure 2: Global oil reserves -conventional versus unconventional resources (Prestine, 2016)

The literature is replete with studies (Ouyang and Aziz, 2000; Santim et al., 2017; Thaker and Banerjee, 2015; Abdul-Majeed, 1996, 2000) focusing on air-water two-phase flows. A handful of these studies (Abdulkadir et al., 2016; Al-Safran et al., 2015; Al-Safran, 2009a) address mainly the flow behaviour of medium viscosity liquids (i.e. viscosity < 1 Pa.s). However, there is a severe dearth of studies and data addressing high viscosity oils (i.e. viscosity > 1 Pa.s). We briefly review some of some these studies in Table 1.

Table 1: Summary of experimental studies high viscosity oil-gas flow

Pioneering research work was conducted by Weisman et al., (1979) on the effects of fluid properties on two phase flow pattern transition. The investigation was carried out in a 6.1-m long horizontal pipe with internal diameter of 0.012 -0.05-m. Air and water-glycerol mixtures with liquid viscosity range of 0.075-0.150 Pa.s were used as the test fluids. It was concluded that the effects of liquid viscosity on the observed flow pattern transitions were negligible.

Andritsos et al., (1989) experimentally studied the effects of liquid viscosity on gas-liquid slug flow initiation in 0.0252-m and 0.0953-m ID horizontal pipes. A mechanism for viscous liquids was proposed noting that that slugs arise from small-wavelength Kelvin-Helmholtz (KH) waves. The proposed mechanism was reported to have shown a good agreement with experimental results.

Contrary to the findings of (Weisman et al., 1979), (Nadler and Mewes, 1995) conducted an experimental investigation in a 0.059-m ID horizontal pipe to study the effects of liquid viscosity on the phase distribution of slug flow. They noted that the average liquid holdup within the slug unit and the elongated bubble region increases with increase in liquid viscosity. The viscosity range for their experimental study was from 0.014 - 0.037 Pa·s with the other fluid physical properties being kept constant.

Gokcal (2006, 2008) studied the effects high liquid viscosities on two phase flow slug features; slug translational velocities, drift velocity, slug length and slug frequency. His investigation was conducted in a 0.0508-m ID horizontal flow loop of 19-m long for which oil viscosity ranging from 0.18-0.587 Pa.s and air were used as experimental test fluids. New closure relationships for the prediction of the slug flow features taking into account viscosity effects were proposed. Using the same test facility and experimental flow conditions, further work on two phase slug flow in high viscosity liquids was conducted by Al-Safran, (2009b, 2009a) and (Kora et al., 2011). While Al-Safran, (2009b and 2009a) developed new correlations for the prediction of slug liquid holdup and slug frequency, Kora et al. (2011) proposed a correlation from dimensional analysis for the prediction of slug liquid holdup in horizontal pipe.

Additional works on high viscous liquids in horizontal pipes were conducted by (Foletti et al., 2011; and Farsetti et al., 2014). While (Folettiet al.(2011) experiment were conducted using oil viscosity of 0.896 Pa.s in a 0.022-m ID, Farsetti et al. (2014) used an inclinable rig with 0.028-m ID using oil viscosity of 0.9 Pa.s. Both studies presented new data-sets on high-viscosity oil multiphase pipe flows which were compared with those from several empirical and theoretical models. The results of comparison were found to exhibit some discrepancies.

More recently, experiments were carried out using relatively high liquid viscosity ranging from 0.07 – 7.0 Pa.s by (Zhao et al., 2015; Zhao, 2014) and (Archibong, 2015). Their studies were conducted in both 0.0762-m ID horizontal pipe and 0.025-m ID inclinable test facility. Based on their investigation, a dominant intermittent flow region as viscosity increases was observed. While Zhao (2014) developed a correlation for the prediction of slug frequency, Archibong (2015) developed correlations for the prediction of slug frequencies, slug liquid holdup and distribution parameter C_o.

The most intrinsic and significant parameters associated with slug flow pattern are the gas and liquid phase distribution, gas bubble and liquid transit frequency and size (i.e. slug length), the velocity of liquid and its fluctuating components, the turbulent transport characteristics of interfacial mass and energy. However, slug length is the most critical slug flow characteristics needed for proper design and safe operation. For example, average slug length is important and preferred (over slug frequency) as an input parameter in mechanistic models to predict liquid holdup and pressure gradient. Furthermore, long slugs often cause operational problems such as flooding of downstream facilities, severe pipe erosion and corrosion, pipeline structural instability, as well as production loss and poor reservoir management due to unpredictable wellhead pressures.

It has been reported by (Cook and Behnia, 2000) that slug length characterised by intermittency and irregularity are significant for two reasons. The first been its need as a closure relation for the calculations of liquid holdup and pressure drop by existing mechanistic models such as those of (Dukler and Hubbard, 1975; Taitel and Barnea, 1990). Secondly and most importantly, the statistical distribution of slug length is needed by a pipeline designer for the design of slug catcher and top side processing equipment. A number of researchers (Romero et al., 2012; Xin et al., 2006; Barnea and Taitel, 1993; Heywood and Richardson, 1978) have reported that liquid slug lengths are constant for over a wide range of mixture velocities for in horizontal pipelines. A summary of measured slug lengths by different researchers is presented Table 2 below.

Table 2: Summary of measured slug length by some researchers

Considerable number of models have been developed for the prediction of slug length from different experimental data source, ranging from simple correlations like those proposed by (Brill et al., 1981; Norris, 1982; Scott et al., 1989; Gordon and Fairhurst, 1987; Losi et al., 2016 and Al-safran et al., 2011) to more intricate ones like that by (Wang, 2012). Slug length as estimated by the existing prediction correlations as presented in Table 3 below are expressed by a limited number of flow parameters such as pipe diameter and mixture velocity. However, recent investigations as carried out by (Zhao, 2014; Baba, 2016; Archibong, 2015; Gokcal, 2006; Al-Safran et al., 2015) have shown that the pipe length and diameter, densities and most importantly the viscosities of the liquid phase considerably influence slug flow characteristics. liquid viscosity effects of on slug length have been investigated by (Al-safran et al., 2011; Wang, 2012; Gokcal, 2008 and Losi et al., 2016). All these authors have unanimously concluded that slug length has significant dependency on the liquid viscosity and decreases with increase in liquid viscosity. In addition, these studies are however all limited to viscosity range less than 1.0 Pa s and were conducted in smaller diameter pipelines making it imperative for further investigation.

The present study provides new experimental dataset for high viscosity oil-gas two-phase flow for oil viscosity ranging from 1.0 – 5.5 Pa. s. This compliments and extends the viscosity range of existing works (as highlighted in Table 1). Furthermore, we propose a new closure relationship for the prediction of slug length in horizontal pipe. To achieve this, data collected from the Heavy Oil 3-inch Test Facility of the Oil & Gas Engineering Centre, Cranfield University and the published data of (Gokcal, 2008).Viscosities ranging between 0.2 and 0.6 Pa.s were utilized. These will significantly contribute to the literature and data on heavy oil as well as provide a new phenomenological based closure relationship for highly viscous oil flow simulations. Additionally, more and more companies are extracting from more unconventional reserves and the information on slug length will help to design processing and transport facilities.

Table 3: Summary of existing correlations in the literature for slug length

1.2 Slug Flow evolution and initiation criteria

Slug flow is generally classified as hydrodynamic slugging or terrain slugging (severe slugging). For horizontal or nearly horizontal pipes, though slugs can be generated due to pigging and ramping up, it is generally accepted that the onset of slugging is caused by two mechanisms; the natural growth of interfacial instabilities of gas liquid interface of stratified flow (*i.e. Kelvin-Helmholtz Mechanism)* and/or the accumulation of liquid at valleys of hilly terrain-induced pipelines characterized with sections of different inclinations, widely known as *terrain slugging*. (Lin and Hanratty, 1987 and Woods et al., 2006)have also noted wave coalescence at high gas flow rates in horizontal pipes as an important mechanism in the formation of slug. Taiteland Dukler.(1976) reported that *Kelvin Helmholtz* instability drives a continuous growth of a small-amplitude long wave into a fully formed slug.

A number of researchers have reported the mechanisms connected with slug initiation and the criteria necessary for the transition of stratified to slug flow ranging from very comprehensive investigations such as the works of (Taitel and Dukler, 1976; Kordyban and Ranov, 1970; Wallis and Dodson, 1973; Ujang et al., 2006 and Lin and Hanratty, 1986) to preliminary work like (Dinaryantoa et al., 2017; Thaker and Banerjee, 2015). A summary of slugging criteria based on the instability analysis as reported by these researchers is presented in Table 4. However, it is important to note that the above mentioned slug initiation mechanism from stratified flow have not been validated with high viscosity liquid (i.e. viscosity > 0.6 Pa.s). Zhao (2014), Archibong (2015) and Baba (2016) etc. reported that no stratified flow in their investigations.

Table 4: Summary of existing models for onset slugging criterion

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1.3 Physical descriptions of the effect of high viscosity

Two important concepts in slug flows are the shedding rate and pick-up rates. On the basis of shedding and “pick-up” processes, slug flow can be classified into three. Firstly, when the pick-up rate is larger than the rate of shedding Under such conditions, the resulting slug experiences continuous growth. Secondly, when the rate of “pick-up” rate is equal to the rate of shedding, the resultant slug becomes fully developed as such the slug length stabilises. However, when the rate of pick-up is less than that of the shedding rate, the slug under this condition dissipates. This third condition better explains the characteristics of slug length for very viscous liquids in which shedding exceeds pick-up. A reason for this occurrence could be the increased forces of cohesion as viscosity increases. To gain insight on the interaction between the film and the slug front, A physical model for minimum slug length was developed by (Dukler and Hubbard, 1975) based on the interaction between the film and slug front simulated in a conduit flow into a large reservoir as illustrated in Fig. 3(a). With the separation of liquid from the film to the slug front, a recirculation process is achieved. This is formed between the separation point and a reattachment point also known as the slug mixing zone. The author noted that the minimum stable slug length in horizontal pipes were 20D though, their experimental data showed slug lengths were in the range of 20-40D.

According to researchers such as (Barnea and Brauner, 1985 and Taitel et al., 1980), a minimum slug length of 32D was obtained from experimental investigation in a horizontal test facility. Two hydrodynamic parameters according to their model can be deduced to control minimum stable slug length; the film height and the length of the slug-mixing zone. The effects of liquid viscosity is observed to affect both parameters as noted by (Al-safran et al., 2013). The author proposed a physical model for high-viscous-liquid slug as illustrated in Fig. 3(b) in which the height of the film in front of the slug is thick, suggesting a shorter mixing region and a reattachment distance resulting in shortened slug length to achieve a fully developed velocity profile.

(a)

(b)

Figure 3: (a) Physical model minimum slug length in light oil, (Dukler and Hubbard, 1975) (b) physical model minimum slug length in high viscosity oil, (Al-safran et al., 2013)

2 Experimental Setup

2.1 Test facility description and measurement procedure

The experimental setup used for this investigation as shown in the schematics presented in Fig. 4 is located at the Oil and Gas Engineering Centre Laboratory of Cranfield University. The experimental flow facility is comprised of the following core sections: the fluid (oil, air and water) handling section, test measurement/observation section and the instrumentation and data acquisition section. The multiphase flow test facility consists of a 0.0762-m-ID horizontal pipe built using transparent Perspex pipe with an L/D ratio of 223. Researchers like (Baba, 2016; Baba et al., 2017; Archibong, 2015; Okezue, 2013 and Zhao, 2014;) have previously used this facility for related study.

2.1.1 Fluid handling section

Mineral oil (i.e. CYL680) used as the liquid phase is stored in a steel tank of 2-m^3 capacity. It is fed into the main test line through a T-junction (See Fig. 5) using a Progressive Cavity Pump (PCP). Metering of the oil flow rate is done using a commercial Coriolis flow meter with an accuracy of ±0.035% at the inlet. Prior to an experiment, a recirculation of the oil in the tank is done via a by-pass aimed towards achieving a uniform oil viscosity. A refrigerated bath circulator manufactured by Thermal Fisher is used for regulating the temperature of the oil. The temperature range of the circulator is from 0 to +50 °C, with an accuracy of ± 0.01 °C., The oil contained in the tank is either cooled or heated to a desired temperature over a period of time by virtue of changing the temperature of the glycol and hence viscosity of the liquid contained in the tank. It is worth noting that though the mineral oil (CYL680) used for this investigation were specified by manufacturers, there was need to validate their claims before commencing experimental runs. The viscosity of the oil was measured in the laboratory and the result compared well with manufacturer's specifications data as presented in Fig. 6.

Figure 4: Schematic of experimental test facility

Figure 5: Pictorial view of test facility injection point.

Figure 6: Comparison of measured viscosity and manufacturer's data

A 2.5-m^3 cylindrical tank is used for storage of water at room temperature supplied from a tap in the laboratory. A variable speed progressive cavity pump (PCP) with maximum capacity of 2.1 m^3/hr and a maximum discharge pressure of 10 barg is used for pumping the water into the 3-inch test facility. The rate of water flow is metered using an electromagnetic flow meter with a range of 0–21 m^3/hr.

Air is used as the gas phase was supplied from a screw compressor with a maximum supply capacity of 400 m^3/hr. In order to avoid pulsating supply of air to the test facility, the air from the compressor is first discharged into a 2.5-m^3 air tank before delivery to the test line where it is regulated to about 7 barg. The flow rates of air were metered using two flow meters: 0.5-inch vortex flowmeter and 1.5-inch vortex flow meter, ranging from 0–20 and 10–130 m^3/h respectively. It is filtered then injected into the main test line using a 2-inch steel pipe about 150 pipe diameters upstream of the test facility's observation section as shown in Fig. 5.

2.1.2 Measurement and observation section

The test measurement/observation section is located 14-m downstream from the test fluid inlet pipe. The mixture of the two phase flow (i.e. oil and gas) is achieved at the T-junction upon injection through V4 and V6 as shown in Fig. 5. This is the point where the multiphase flow starts to develop.

2.1.3 Instrumentation and data acquisition section

The separator, gamma densitometer (described in details in 2.3 below) and the heater/chillers (earlier described in 2.1.1) are the three main unit operations equipment used in the for this investigation. The separator positioned at the end of the pipeline is a rectangular shaped steel tank with viewing windows is used for the collection and separation of the multiphase fluid into phases. The test fluids are allowed to settle for 48 hours. Air is vented to the atmosphere, Oil and water are transferred to their respective storage thanks and reused.

The temperature of the test fluids is measured using a J-type thermal couples with an accuracy of ±0.1°C placed at different locations along the test line. while differential pressure transducers installed at 4-m and13-m downstream of the test line were used for pressure measurement. Acquired data from the temperature sensors, flowmeters and differential pressure transducers are saved to a Desktop Computer using a LabVIEW-based system. This system comprised of a National Instruments (NI) USB-6210 connector board interface that output signals from the instrumentation using BNC coaxial cables connected the desktop computer.

2.2 Test Matrix

A summary of the experimental test fluid properties and the adopted test matrix used for this investigation are presented in Table 5. The uncertainties in the measurement of superficial gas and liquid velocities, liquid hold and viscosities as presented in Table 6 were obtained based on manufacturers' specification of flow meters, viscometer, and gamma sensor. This is in agreement with values obtained upon carrying out repeatability tests to ascertain accuracy of the values.

Table 5: Experimental test matrix and fluid properties

Table 6: Uncertainties in measurements

2.3 Instrumentation and calibration

A fixed single beam gamma densitometer as illustrated in Fig. 7 was used for the measurement of the phase fraction. This is comprised of a single energy source block and a Sodium Iodide (NaI) scintillation radiation detector. A 5.5 Gigabecquerel (GBq) Caesium-137 radioisotope is contained in the source block housed within a lead radiation protection shield and further encased in stainless steel. The Caesium-137 radioisotope in the instrumentation is a dual-energy source emitting gamma rays in two broad photon energy levels; the gamma radiation transmitted is the source of the 662-keV high-energy level while scattered gamma radiation is the source of the lower energy level range of 100 keV–300 keV. At a sampling rate of 250 Hz, the sodium iodide (NaI) scintillation radiation detector was used to measure two separate sets of gamma attenuation data for the high and low energy levels. A proprietary Data Acquisition System (DAS) was used for voltage signal acquisition and a ICP i-7188 programmable logic controller which is used to convert the raw voltage to gamma counts signals (i.e. counts are the remainder of the attenuation signals after absorption by the media it passes through).

Figure 7: Pictorial representation of gamma ray densitometer used as instrumentation

Eq. (1) below represents the Beer-Lambert equation used for linear attenuation coefficients computation and hence, the liquid holdup. For an empty pipe, the gamma radiation beam's intensity remains unchanged inside the pipe because is virtually zero in comparison.

$$\lambda_L = \left[\frac{ln\left(\frac{I_M}{I_A}\right)}{ln\left(\frac{I_L}{I_A}\right)} \right] \tag{1}$$

Where

I_M = average gamma count obtained from liquid-gas mixture in the pipeline

I_A = average calibration gamma count obtained for empty pipe (i.e.100% Air)

I_L= average calibration gamma count obtained for pipe containing pure liquid

λ_L= Liquid Hold Up

A typical plot from of the Gamma Densitometer liquid holdup time series exhibits an intermittent behaviour for slug flow as presented in Fig. 8 characterized by crests and troughs. While the trough region is suggestive of the passage of liquid slugs, the crest regions are indicative of the slug film region. The holdup time traces obtained from two gamma densitometers positioned at 103D and 124D (see Fig. 9) downstream of the oil injection point were used for the slug translational velocity data collection. This is achieved by carrying out a cross-correlation using the MATLAB signal processing toolbox.

Figure 8: A typical gamma densitometer time series liquid holdup plot for dual Gamma Sensor

Figure 9: Diagrammatic representation of the Gamma Source installed on the test facility.

From Figure, if the distance between the two gamma densitometers is represented by Δl_{Gamma} and assuming the arrival time of the slug front at first and second gamma densitometers are denoted by T1 and T2 respectively, obtained by virtue of the passage of a slug body through the cross sectional area of the pipe where the gamma detectors are located. Then the translational velocity is given by;

$$V_T = \frac{\Delta l_{Gamma}}{T_1 - T_2} \tag{2}$$

Slug length is obtained by multiplying the time difference between the period of passage of the slug body through the two gamma densitometer and the translational velocity of the slug obtained from Eq. (2). Therefore slug length L_s,

$$L_s = V_T \times \tau \tag{3}$$

where τ is the time or temporal lag between the signals registered by the two densitometers. It is obtained by cross-correlation and explained in section 2.5. Owing to the randomness in the gamma photon emissions obtained from the source (i.e. caesium-137), there was a need to determine the statistical uncertainty in the gamma beam measurements. The uncertainty in this case is inversely proportional to the measurement time adopted for experimental runs This is described by the equation:

$$SU = \frac{1}{S\sqrt{N_{Count}}} \tag{4}$$

where SU is the statistical uncertainty. It depends on the sensitivity (S) of the densitometer as well as that of the gamma attenuation data (N_{Count}) size measured for the multiphase flow (i.e. oil-gas) mixture over a certain period of time. Therefore, sensitivity is the relative difference between the response of the gamma densitometer to pure liquid and to pure gas:

$$S = \frac{I_G - I_L}{0.5(I_G + I_L)} \tag{5}$$

Where I_G and I_L are respectively the mean gamma count values obtained when the gamma beam densitometer was calibrated using 100% air and 100% oil. As was reported by Okezue (2013), the current gamma densitometer attenuation data recordings gave an average statistical uncertainty of 1.70%. Readings were taken at a mean measurement time of 70s per experimental run. Other sources of error in the measurements are systematic error in the Sodium Iodide (NaI) scintillation radiation detector and errors arising from the dynamic fluctuation of the gas–liquid two-phase flow field in the cross-sectional area of the measurement pipe section. It is estimated that the sum total of the error sources mentioned result in a maximum of 5% uncertainty in the slug lengths measured by the gamma densitometer. In view of this, error bars have been added to relevant figures to account for these effects.

2.4 Data Processing

The randomness characteristics feature of gamma radiation distorts the output signal, thus providing an inferior signal quality on the receiving end and hence, the need to filter the raw output signal in order to improve data quality. For the purpose of this study, the analysis was conducted using MATLAB to filter the output signals from the gamma densitometer. The "smooth" function was used. It utilizes a moving average filter (average of 8) aimed towards noise reduction. Presented in Figs 10(a) and (b) are typical example of raw and filtered signal output from the gamma densitometer.

Figure 10: (a) Raw signal output from gamma photon counts. (b) Sample of a filtered signal output.

2.5 Cross-correlation Procedure

Cross-correlation is a standard method which measures the degree to which two signals correlate with one another with respect to the time displacement that exist between them. The cross-correlation for similar and identical signal tends towards unity or unity and if they are dissimilar, the cross-correlation tends to zero or even zero. Assuming two-time series, $X(t_n)$ and $Y(t_n)$, where n=0, 1, 2, 3…. N-1, then the cross correlation coefficient is defined as;

$$R_{xy}(\tau) = \frac{C_{xy}(\tau)}{\sqrt{C_y(0)C_y(0)}} \tag{6}$$

$$C_{xy}(\tau) = \frac{1}{N-\tau} \sum_{n-1}^{N-\tau} X(t_n)\, Y(\tau + t_n), \tag{7}$$

Where τ is the temporal lag.

The filtered signal output from both gamma densitometers are then used for performing a cross-correlation. It is worth noting that a better correlation is achieved if the output of the cross correlation function result tends towards “1” and no correlation if it tends towards “0”. Fig. 11 shows a clear cross-correlation between the two-time series signal output.

Figure 11: Cross-Correlation results between Gamma 1 and Gamma 2.

3 Results and discussion

3.1 Experiments with air and water

Initial experiments were carried out using air and water ($\mu = 0.001$ Pa.s). Since data for air/water mixtures are widely available, comparing our slug lengths with those in those in the literature will ensure the reliability of experimental data collected from the experimental rig. Fig. 12(a) shows the slug lengths we obtained plotted as a function of mixture velocity. It indicates that the measured slug length is approximately 24-36D with a mean length of 30.6D. This agrees with the work of Pan (2010) who reported a mean length of 30D with an approximate length of 20-40D for air-water experiments in a 0.0762 m ID horizontal pipe. His investigation further revealed a mean length of 24D for 0.004 Pa.s oil-air experiments. It is worth noting that experimental observations by previous authors (Nicholson et al., 1978; Barnea and Brauner, 1985; Fabre and Line, 1992; Dukler and Hubbard, 1975) for air–water systems in upward vertical and horizontal flows suggest that the average stable liquid slug length is largely insensitive to the gas and liquid flow rates and depends mainly on the pipe diameter. Previous authors also reported measured slug lengths within the range of 15—40D with an average slug length of 30D. We plotted the distribution of slug lengths obtained at $V_{sg} = 0.3 - 7\ m/s\ and\ V_{sl} = 0.2 - 0.4\ m/s$ in Fig. 12(b) and as can be seen, a lognormal curve describes the experimental data quite well. This is consistent with the findings of (Nydal et al., 1992) who also reported that their experimental slug lengths were log-normally distributed and right-skewed.

Figure 12: (a) Measured slug length as a function of mixture velocity (b) Slug length distribution and log-normal fit for flow conditions investigated (Vsg=0.3-7m/s and Vsl=0.2-0.4m/s)

3.2 Flow Pattern Characterization for High Viscosity Oil Gas Flows

Flow pattern characterization for this investigation was achieved by using High Speed Video camera. Presented in Table 7 are the flow patterns observed for this study. There are; plug flow, slug flow, pseudo slug and wavy annular flow patterns. Plug flow and slug flow are both termed as “intermittent flow”. To begin with, the intermittent flow was observed to dominate the entire flow regime and this is line with previous findings (Gokcal, 2006, 2008; Zhao, 2014; Archibong, 2015 and Baba et al., 2017). It is a flow pattern characterised by an intermittency i.e. the alternation of series of liquid slugs (plugs) largely separated by gas pockets. The distinctive parameter of slug flow pattern from plug flow, is the presence of pronounced gas entrainments in the former than the latter. The intermittent flow pattern is closely followed by a transition flow pattern termed as “pseudo slug” (i.e. transition from intermittent to wavy-annular flow pattern). It is mostly characterised by large energetic travelling waves. Further increase in the gas superficial velocity results in the formation of wavy-annular flow pattern characterised by high gas momentum which sweeps most of the liquid phase around the pipe walls with a a rolling wave at the interface. It is worth noting that a temporary emulsion formation was observed during the course of this investigation at relatively very high superficial gas velocities. This occurrence is due to the agitation of the gas phase (i.e. its tendency in displacing the liquid phase leads to the gas to been entrained in the liquid phase) and viscosity of the liquid phase. In addition, the high viscosity property of the liquid makes it difficult for the entrained gas to escape easily and this explains the higher entrainment characteristic feature of slug formation in highly viscous liquid.

Table 7: Snapshots of observed flow patterns

3.3 Slug Length for High Viscosity Liquid

Fig. 13(a) shows the measured mean slug length plotted as a function of gas superficial velocity for oil superficial velocities (0.06~0.3 m/s) for varying oil viscosities. The plot shows a strong dependence of slug length on liquid viscosity as slug body length decreased with increase in liquid viscosity. The measured length of slug was in the range of 4-9D with an of average length of 6D as against 8-14D,15-40D,15-27D,12-30D 10-34D and 15-27D ranges obtained respectively by (Al-safran et al., 2011; Dukler and Hubbard, 1975; Nicholson et al., 1978; Nydal et al., 1992; He, 2002 and Xin et al., 2006). A comparison of mean slug length plotted as a function of mixture velocity for this study and (Al-safran et al., 2012) is presented in Fig. 13(b). Most researchers (Hernandez, 2007; Pan, 2010; Gokcal, 2008) unanimously reported that slug length are generally insensitive to flow conditions (i.e. changes in gas superficial velocity and liquid superficial velocity). The trend observed corroborates the findings of (Hernandez, 2007; Pan, 2010; Gokcal, 2008) as can be seen illustrated in Fig.15 where there is an irregular nature of the data relative to the uncertainties of time of passage of the slug body.

Figure 13: (a) Measured slug length versus superficial gas velocity for different superficial liquid velocity Vsl=0.06-0.3m/s. (b) Mean Slug Length as a Function of Mixture Velocity. Error bars were calculated from the uncertainty equation (i.e. Eq. 12) given in Appendix.

Liquid slug length data are generally described by positively skewed distributions (i.e. log-normal distribution) according to (Van-Hout et al., 2001; Gokcal, 2008; Nydal et al., 1992). In view of this, Easy Fit software 3.0 was used to determine the mean and standard deviation of the Log-Normal distribution. Presented in Fig. 14 is the comparison between experimental result and Log-Normal distribution which exhibited a good match.

Figure 14: Comparison of experimental result for slug length and Log-Normal distribution.

4 Relationship for Slug Length

Slug length as deduced from our experimental observations and published works is a function of density, velocity, pipe diameter and fluid properties (i.e. Eq. 8).

$$\frac{L_s}{D} = f\left(\rho_m, V_m, D, \mu_{L,}\ g\right) \tag{8}$$

Carrying out dimensional analysis by applying the Buckingham Pi-theorem yielded the following dimensionless groups – the mixture Reynolds number, mixture Froude number and viscosity number:

$$\frac{L_s}{D} = f\left(Re_m, Fr_m, N_\mu\right) \tag{9}$$

Where Re is the Reynolds number defined as $\frac{\rho_m V_m D}{\mu_L}$. It's use as a candidate for correlation is consistent as it captures inertia changes prompted by changes in fluid superficial velocities relative to viscous forces. In addition, the Reynolds number provides information necessary for categorising the flow of the two-phase mixture into the laminar or turbulent flow regions. It should be noted that μ_L was used because $\mu_L \gg \mu_g$ thus making μ_g negligible. The Froude number represented by $\frac{V_m}{\sqrt{gD}}$ is a dimensionless number which is used in hydrodynamics studies to indicate the influence of gravity on fluid motion. It is the ratio of inertial forces of pressure driven gas/liquid flow to the opposing gravitational force. Finally, N_μ is the viscosity number, which is defined as $\frac{\mu_L}{\rho_m g^{1/2} D^{3/2}}$ captures the overriding influence of oil viscosity on slug length. Assuming the nature of the functional dependency of slug length on the dimensional groups is in the form of a power law relationship, we can express Eq. (9) as follows:

$$\frac{L_s}{D} = \alpha\, Fr_m{}^{\beta}\ N_\mu{}^{\gamma}\, Re_m{}^{\delta} \tag{10}$$

Where the factor α and the indices β, γ, and δ are constants to be determined upon correlating with the acquired experimental dataset using multiple non-linear regression. Therefore, the new correlation for new mean slug length for high viscosity oil-gas flow is proposed as:

$$\frac{L_s}{D} = 3.35\, Fr_m{}^{0.03}\ N_\mu{}^{-0.2}\, Re_m{}^{0.1} \tag{11}$$

Eq. 10 was obtained using the current data and those of (Gokcal, 2008). Notable in the equation is the relative insensitivity of dimensionless slug length Ls/D to the mixture Froude and Reynolds numbers. This is consistent with the work of Al-Safran et al. (2013) in which their slug length correlation for medium viscosity oils was only dependent on the dimensionless viscosity number N_μ. In their proposed correlation, N_μ was raised to the exponent -0.321 compared with the -0.2 in Eq. 10. However, slug length decreases monotonically with increase in oil viscosity meaning that a point could be reached where further increasing the viscosity will have little or no effect on the length of the liquid slug.

4.1 Validation of proposed correlation

Performance of the proposed slug length prediction model was examined against selected slug length correlations in the literature. Correlations whose predictive performance were evaluated include; (Brill et al., 1981; Norris, 1982; Scott et al., 1989; Wang, 2012; Al-safran et al., 2013). Results presented in Table 15 below shows that all the existing prediction correlations found in the literature over-predict the average slug length with huge discrepancies. The correlations of (Brill et al., 1981; Norris, 1982; Scott et al., 1989) over predict obtained experimental data with very wide error margin. This can be attributed to the fact that there were developed using conventional fluids (i.e. low viscosity liquids (<0.01 Pa.s). Al-safran et al. (2013) unlike Wang, 2012 performed fairly well even though both were developed and tested using dataset from the same viscosity range. This can be credited to the fluid properties inherent in Al-safran et al., 2013 as against Wang, 2012. A comparison of experimental measurements against the best perfrming predicted models as highlighted in Table 8 is presented in the Figs 15(a)-(c).

(a)

(b)

(c)

Figure 15: Cross-plot of predictive model predictions for best performing correlations against experimental measurement (a) Current (b) Al Safran (2013) (c) Brill (1981)

Fig. 16 shows simulations carried out using Eq. (9) to predict the effect of oil viscosity and mixture Reynolds number on the slug length. Comparisons were made with the experimental data of Al-Safran et al. (2013) who performed their experiments in a 0.0508-m pipe with oil viscosities of 0.18–0.59 Pa.s. Also, the current data was compared and as can be seen, there is good agreement as all were within the $\pm$20% error margin shown in Fig. 15(a).

Figure 16: Use of Al-Safran (2013) and current experimental data concerned with oil viscosities ranging from 0.18–6.00 Pa.s to validate Eqn. (9)

Finally, Table 8 shows the results of statistical analysis carried out on the current data, using the proposed correlation Eq. (9) and those of Brill (1981), Norris (1982), Scott (1989), Wang (2012), and Al-Safran (2013). The statistical parameters $\varepsilon_1 - \varepsilon_6$ in the table are the relative error, average relative error, absolute relative error, standard deviation about the relative error, average actual error, and the standard deviation of the actual error respectively. Their mathematical relationships are defined in the Appendix. These show that the new correlation produced the least value for each of the statistical parameters indicating improved prediction on the previous ones and this is due to the fact that previous correlations were obtained with data at far lower viscosities than those used in our experiments. This underlines the importance of viscosity and its dominance in closure relationship predictions which can have a profound effect on the accuracy of flow simulators for heavy oils. In summary, the comparative analysis reveals the need for a slug length prediction correlation in high viscous pipe flow systems.

Table 8: Statistical evaluation of surveyed slug length correlations

5 Conclusion

A new set of experimental data for two-phase flow slug length using high-viscosity mineral oil as the liquid phase and air as the gas phase. The experiments were conducted in a 0.0762 m ID horizontal pipe using a fast-sampling gamma densitometer) at a frequency of 250Hz. Results show that slug length decreases with increasing liquid viscosity and is relatively insensitive to changes in the individual superficial liquid viscosities. However, we find that slug length is very sensitive to changes in liquid viscosity. The minimum 32D slug length proposed by researchers (Barnea and Brauner, 1985; and Taitel et al., 1980) for liquid slug length in horizontal pipeline was found to be much shorter once viscosity exceeds 0.1 Pa.s. For the current viscosity range, 1 – 5.5 Pa.s, the mean slug length was approximately 6D which is not far from the 10D obtained by Al-Safran et al. (2013) for the range of 0.18 – 0.59 Pa.s. A performance evaluation of existing correlations was carried out against the present data and wide discrepancies were revealed. This can be attributed to the use of oil data lower than 1 Pa.s to derive these models. As a result, a new correlation for slug length was obtained using the current data with the correlation exhibiting a better prediction of the dataset. It will therefore serve as a significant improvement for the prediction of heavy oil slug length than previous ones based on low viscous oils.

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7 Appendix

7.1 Error Analysis

The uncertainty in determining the slug length is given as a relative error which depends on the relative errors in the translational velocity and the time lag between the two gamma densitometer readings as follows:

$$\frac{\delta L_S}{L_S} = \sqrt{\left(\frac{\delta V_T}{V_T}\right)^2 + \left(\frac{\delta \tau}{\tau}\right)^2} \qquad (12)$$

where δ is the uncertainty in the quantity that follows it. For translational velocity, its uncertainty is related to the sensitivity S of the gamma readings given in Eq. 5. On the other hand, the uncertainty in

τ is fixed by the cross-correlation procedure which is limited by the sampling rate of each densitometer which in this case is 250 Hz (or 1/250 = 0.004 s).

7.2 Statistical Parameters

Six statistical parameters were used to evaluate the performance of predictive correlations relative to the experimental data acquired. These parameters were also used by several researchers such as (Gokcal et al., 2009; Al-Safran, 2009a; Kora et al., 2011; Zhao, 2014) and are evaluated based on two types of errors; actual and relative error defined in Eqs. (15) and (18) respectively. Results are given in Table 8 and the best performing correlations are those with the least magnitude of the statistical parameter concerned. They are:

$$\varepsilon_i = \frac{y_{predicted} - y_{measured}}{y_{measured}} * 100 \tag{13}$$

$$\varepsilon_j = y_{predicted} - y_{measured} \tag{14}$$

Based on the error margin from estimated actual error and relative error above, six other statistical parameters are defined from Eqs. (15) to (20)

The average relative error is given as:

$$\varepsilon_1 = \frac{1}{N}\sum_{i=1}^{N} y_i \tag{15}$$

The absolute of average relative error is given as:

$$\varepsilon_2 = \frac{1}{N}\sum_{i=1}^{N} |y_i| \tag{16}$$

While standard deviation about the relative error is given by:

$$\varepsilon_3 = \sqrt{\frac{\sum_{i=1}^{N}(y_i - Y_1)^2}{N-1}} \tag{17}$$

The average actual error

$$\varepsilon_4 = \frac{1}{N}\sum_{j=1}^{N} y_j \tag{18}$$

The absolute of the average actual error is given by

$$\varepsilon_5 = \frac{1}{N}\sum_{i=1}^{N}|y_j| \tag{19}$$

514 And finally, the standard deviation of actual errors is given by:

$$\varepsilon_6 = \sqrt{\frac{\sum_{j=1}^{N}(y_j - Y_4)^2}{N-1}} \tag{20}$$

515 The average relative error ε_1 and the average actual error ε_4 are the agreement between the
516 predicted and measured parameters. Positive numbers indicate over-estimation of the parameter and
517 vice versa. Individual error can be either positive or negative, and they can cancel each other, masking
518 the true performance. The average absolute percentage relative error ε_2 and the average absolute
519 actual error ε_5 do not have masking effect. However, they indicate how large the error is on the
520 average. The standard deviation ε_3 and ε_6 indicate the degree of scattering with respect to their
521 corresponding average errors ε_1 and ε_4.

522 **8 Nomenclature**

Symbol	*Denotes*	*Units*
A	*Area*	m^2
C	*Constant*	
D	*Pipe diameter*	*m*
Fr	*Froude number*	
f_s	*Slug Frequency*	s^{-1}
g	*Acceleration due to gravity*	$m.\ s^{-2}$
L	*length*	*m*
$h_{G,L}$	*Height*	*m*
N_μ	*Viscosity number*	
H_L	*Holdup*	
H_F	*Average film holdup*	
H_S	*Average slug holdup*	
N_f	*Inverse viscosity number*	
Re	*Reynolds number*	
St	*Strouhal number*	
V_M	*Mixture Velocity*	*m/s*
Ls	*Liquid slug length*	*m*

V_{SG}	*Superficial Gas Velocity*	*m/s*
V_{SL}	*Superficial Liquid Velocity*	*m/s*
V_T	*Translational velocity*	*m/s*
J_{GL}	*Non-dimensional gas-liquid relative velocity*	
Si	*Wetted perimeter interface*	
Greek letter		
μ	*Viscosity*	*Pa.s*
λ_L	*Liquid holdup*	
ρ	*Density*	*kg/m^3*
$\Delta\rho$	*Density difference*	
τ	*Shear stress*	*Pa*
α	*Void fraction*	
ε_{1-6}	*Relative error*	
Subscripts		
f	*Film zone*	
g	*Gas phase*	
l	*Liquid phase*	
m	*Mixture phase*	
s	*Superficial*	
t	*Translational*	

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Table 1: Summary of experimental studies high viscosity oil-gas flow

Author(s)	Liquid			Gas	Pipe			Parameters Measured	Models/Correlations Proposed
	Type	Viscosity (cP)	Density (kg/m3)	Type	ID (m)	Inclination (Degree)	Material		
Abdulkadir et al., 2016	Oil	525	900	Air	0.067	0	Acrylic	Flow pattern, slug frequency, holdup, slug velocity, lengths of liquid slug and elongated bubble, pressure gradient	N/A
Archibong (2015)	Oil	1000- 7500	916	Air	0.0762, 0.0254	0, 30	Acrylic	Flow pattern, slug frequency, holdup, slug velocity	Distribution parameter, slug liquid holdup, Slug Frequency
Al-Safran et al., (2013)	Oil	587	-	Air	0.0508	0	Acrylic	Slug Frequency	Slug Frequency
Al-Safran et al.,(2005, 2011, 2013)	Oil	181-587		Air	0.0508	0	Acrylic	Slug length	Slug Length
Brito et al., (2013)	Oil	10-180			0.0508			Pressure gradient, flow pattern, translational velocity	
Farsetti et al, (2014)	Oil	900	-	Air	0.0228	0, 5, 10, 15, -5, -15	NA	Pressure Gradient Slug Frequency Slug Holdup	NA
Foletti et al., 2011	Oil	896	886	Air	0.022	0	Plexiglas	Pressure Gradient	NA
Gokcal et al., (2010)	Oil	181-590	-	Air	0.0508	0	NA	-	Slug Frequency
Gokcal et al. (2006)	Oil	181-590	-		0.022	0	NA	Flow pattern	NA
Gokcal (2008)	Oil	181-590	-		0.0508	0	NA	Flow pattern, slug frequency, holdup, slug velocity, drift velocity and slug length	Slug frequency
Kora et al., 2011	Oil	181, 257, 387, 587	-	Air	0.0508	0	Acrylic	Slug Liquid Holdup	Slug Liquid Holdup
Nadler & Mewes (1995)	Oil	14-37		Air	0.059	0		Liquid holdup	-
Schulkes, 2011	Oil	1-590	-	Air	0.019 – 0.1	0 - 80	-		Slug Frequency

Weisman et al., 1986	glycerol-water	75, 150	-	Air	0.012, 0.025, 0.051	0	-	Flow pattern	NA
Wang, 2012	Oil	15, 28, 57	890	air	0.0508	0, 90	NA	Slug liquid holdup and mean slug length	Slug liquid holdup and mean slug length
Zhao et al., 2013	Oil	1000, 3500	916	Air	0.0762	0	Acrylic	Slug Frequency	Slug Frequency

Table 2: Summary of measured slug length by some researchers

Authors	Measured average slug length
(Dukler and Hubbard, 1975)	Ls = 30D
(Nicholson et al., 1978)	Ls = 15-27D
(Barnea and Brauner, 1985)	Ls = 15-40D
(Nydal et al., 1992)	Ls = 12-30D
(He, 2002)	Ls = 10-34D
(Xin et al., 2006)	Ls = 15-27D
(Pan, 2010)	Ls = 24D
(Al-safran et al., 2011)	Ls = 10D
Present Study	Ls = 6D

Table 3: Summary of existing correlations in the literature for slug length

Authors/ Year	**Experimental conditions/ Data Source**	**Correlations developed for slug frequency**	**Comments**
(Heywood and Richardson, 1978)	-	$L_S = \frac{V_m(1+V_T)}{f_s}\frac{H_L - H_F}{H_S - H_F}$	Correlation developed based on observation using Air-Water as test fluids
(Brill et al., 1981)	Alaska Prudhoe Bay field data	$\ln(L_s) = -3.851 + 0.059Ln\left(\frac{V_m}{0.3048}\right) + 5.445\left[Ln\left(\frac{D}{0.0254}\right)\right]^{0.5}$	Correlation only accounted for few parameters (i.e. Mixture velocity and pipe diameter) and was developed based on observation using Air and light oil as test fluids
(Norris, 1982)	Modified (Brill et al., 1981)	$\ln\left(\frac{L_S}{0.3048}\right) = -2.099 + 4.859\sqrt{\ln\frac{D}{0.0254}}$	Simply carried out a modification of the (Brill et al., 1981) correlation and accounted for just pipe diameter.
(Gordon and Fairhurst, 1987)	ID = 0.3048 m, 0.4064 m and 0.508 m	$\ln L_S = -3.287 + 4.859\sqrt{\ln D + 3.673} + 0.059Ln(V_m)$	This correlation accounted for just pipe diameter and mixture velocity and mixture velocity
(Gordon and Fairhurst, 1987)	ID = 0.3048 m, 0.4064 m and 0.508 m and 0.588 m	$\ln L_S = -3.287 + 4.859\sqrt{\ln D + 3.673}$	More data points were utilized for this correlation though accounted for only pipe diameter.
(Scott et al., 1989)	Alaska Prudhoe Bay field data	$\ln L_S = -26.6 + 28.495\left[Ln\left(\frac{D}{0.0254}\right)\right]^{0.1}$	Correlation valid for very large diameter pipe data
(Wang, 2012)	0.0525 m ID pipe, 0.15 to 0.57 Pa.s.	$L_S = \left\{10.1 + \frac{16.8}{1 + Exp[-3.57 * (Ln(N_f) - 5.4)]}\right\}\left[\mathrm{Cos}^\wedge 2\,\theta + \frac{Sin^\wedge 2\theta}{2}\right]D$	Experimental data was sourced from observation using light oil of less than 0.1 Pa.s
(Al-safran et al., 2011)	Air-oil, ID=0.0508 m, 0.181 – 0.589 Pa. s	$\frac{L_S}{D} = 2.63\left[\frac{D^{2/3}\sqrt{\rho_L(\rho_L - \rho_G)}}{\mu_L}\right]^{0.321}$	Accounted for viscosity effects however, only medium oil viscosities were used.
(Losi et al., 2016)	Air-oil; ID = 0.022 m, 0.037 -0.804 Pa s; j_L = 0.1- 0.3 m/s and j_g = 1.3 - 2.2 m/s	$\frac{L_S}{D} = A\left[j_g + \frac{j_{go}^2}{j_g}\right]$ where j_g is the superficial gas velocity corresponding to the minimum slug length and the constant A is a function of liquid properties (details in Losi et al., 2016) while j_{go} is the critical superficial gas velocity	Also accounted for viscosity effects but experiment were conducted in a small diameter pipe.

Table 4: Summary of existing models for onset slugging criterion

Authors/ Year	Onset slugging criterion	Comments
(Wallis and Dodson, 1973)	$V_g - V_l \geq K\left\{\frac{g(\rho_L-\rho_G)h_G}{\rho_G}\right\}^{\frac{1}{2}}$	Based on an experimental and analytical study of transition to slug flow in essentially horizontal rectangular channels geometry with small amplitude waves. K experimentally determined to be 0.5
(Taitel, Y. and Dukler, 1976)	$V_g - V_l \geq K\left\{\frac{g(\rho_L-\rho_G)h_G}{\rho_G}\right\}^{\frac{1}{2}}$ Can be approximated to $J_{GL} = \alpha^{2.5}$	The growth of a finite disturbance on a smooth stratified layer in a horizontal channel was considered. For an infinitesimal disturbance, the value of K will be unity due to the overestimation. Hence (Taitel, Y. and Dukler, 1976) recommended K=$\left\{1-\frac{h_l}{D}\right\}$. The model was observed to work reasonably for horizontal small diameter pipes using air-water flows at atmospheric pressure.
(Mishima and Ishii, 1980)	$V_g - V_l \geq K\left\{\frac{g(\rho_L-\rho_G)h_G}{\rho_G}\right\}^{\frac{1}{2}}$	(Mishima and Ishii, 1980) obtained K to be 0.487 by extension of the stability theory of finite-amplitude interfacial waves as proposed by (Kordyban and Ranov, 1970).This model suits the prediction of transition to slug flow in a rectangular duct well.
(Lin and Hanratty, 1986)	$V_g = K\left\{\frac{gD(\rho_L-\rho_G)h_G}{\rho_G}\right\}^{\frac{1}{2}}$	The application of linear stability theory was explored to explain the onset of slugging. A Good agreement was established between the linear stability analysis and observations of the initiation of slugs in horizontal pipes. K was taken to be $f(\alpha, V_m, V_{sg})$
(Anoda et al., 1989)	$V_g \geq K\left\{\frac{g(\rho_L-\rho_G)h_G}{\rho_G\, dA_l/dh_l}\right\}^{\frac{1}{2}}$ Where K=$\left\{1-\frac{h_l}{D}\right\}$,	A modified form of (Taitel, Y. and Dukler, 1976)
(Barnea and Taitel, 1994)	$(V_G \geq V_L) < K\left\{(\rho_L\alpha - \rho_G\varepsilon)\frac{\rho_L-\rho_G}{\rho_L\rho_G} g\cos\theta \frac{A}{dA_L/dh_L}\right\}^{\frac{1}{2}}$ $K_V = \left\{1 - \frac{(C_{IV}-C_V)^2}{\frac{\rho_L-\rho_G}{\rho_L\rho_G} g\cos\theta \frac{A}{dA_L/dh_L}}\right\}^{1/2}$ $C_{IV} = \frac{\rho_L V_{SL}\alpha + \rho_L V_{SG}\varepsilon}{\rho_L\alpha + \rho_L\varepsilon}$ $C_V = \frac{\left[\frac{\partial F}{\partial \varepsilon}\right]_{Vsl,Vsg}}{\left[\left[\frac{\partial F}{\partial V_T}\right]_{Vsl,\varepsilon} - \left[\frac{\partial F}{\partial V_T}\right]_{Vsl,\varepsilon}\right]}$	Considered a long wavelength interfacial instabilities and their growth. For inviscid flow K=1, for viscous case K=Kv

	$F = -\frac{\tau_{lf}S_l}{A_l} + \frac{\tau_{gf}S_g}{A_g} + \tau_i S_i\left(\frac{1}{A_l} + \frac{1}{A_g}\right) - (\rho_L - \rho_G)gsin\theta$	
(Hideo, 1996)	$V_g \geq K\left\{\frac{g(\rho_L - \rho_G)h_G}{\rho_G\, dA_l/dh_l}\right\}^{\frac{1}{2}}$ Where K=$\left\{1 - \frac{h_l}{D}\right\}^n$	Modified the coefficient (K) value of the (Taitel, Y. and Dukler, 1976) model. This model is best suited for relatively-low pressure flows in large-diameter pipes with n=2
(Chun et al., 1995)	$V_g \geq K\left\{\frac{g(\rho_L - \rho_G)h_G}{\rho_G}\right\}^{\frac{1}{2}}$	A theoretical relationship developed for the wave height in a stratified wavy flow regime using the concept of total energy balance over a wave crest considering the shear stress acting on the interface of two fluids. K was found to be 0.470
(Chang-Kyung and Moon-Hyun, 1996)	$V_g = \left(1 - \frac{h_l}{D}\right)\left\{\frac{\pi\Delta\rho\alpha gDCos\theta}{4Sin\gamma}K\right\}^{\frac{1}{2}}$	A more general expression for the onset of slug criterion derived from singular points and neutral stability conditions of the transient 1-D equations of two fluid model presented. K was given as $1 + \frac{\alpha\rho_g}{\rho_L\varepsilon}$

Table 5: Experimental test matrix and fluid properties

S/N	Density (kg/m³)	Test fluids	Viscosity (cP)	Interfacial tension (25°C, N/m)	Test matrix (m/s)	API gravity
1	1.293	Air	0.017	0.033	0.3-9.0	-
2	≈ 1000	Water	1	0.029	0.06-0.4	-
3	≈ 918	CYL680	1000~6000	0.033	0.06-0.3	22.67

Table 6: Uncertainties in measurements

Measurements	Uncertainty (%)
Superficial liquid velocity	±0.5
Superficial gas velocity	±2.1
Liquid viscosity	± 1
Pressure drop	± 2
Liquid holdup	± 5

Table 5: Snapshots of observed flow patterns

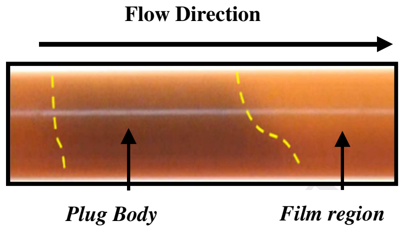
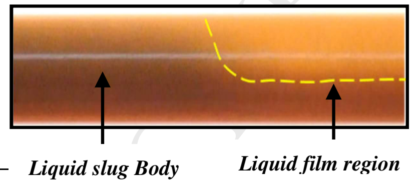
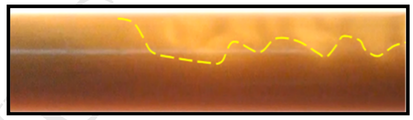
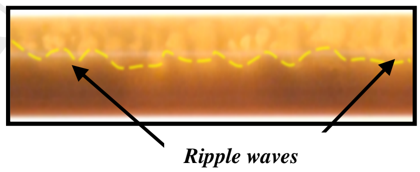
Nomenclature	Flow Condition	Video image
Plug Flow	V_{SL} 0.3m/s, V_{SG} 0.3-0.7m/s	
Slug Flow	V_{SL} 0.3m/s, V_{SG} 0.7-3.0 m/s	
Pseudo Slug Flow	V_{SL} 0.3m/s V_{SG} 3.0-5.0 m/s	
Wavy Annular Flow	V_{SL} 0.3m/s, V_{SG} 5.0-9.0 m/s	

Table 8: Statistical evaluation of surveyed slug length correlations

	Proposed Correlation	Brill (1981)	Norris (1982)	Scott (1989)	Wang (2012)	Al-Safran et al, (2013)
$\varepsilon1$	0.517391	-34.1318	7401.188	10088.98	181.3125	14.4496
$\varepsilon2$	8.468193	46.13764	7401.188	10088.98	181.3125	20.30533
$\varepsilon3$	10.6204	34.29429	1238.391	1888.901	104.2071	18.50914
$\varepsilon4$	-0.15192	-4.55236	761.5418	1061.032	16.29675	2.736121
$\varepsilon5$	1.505312	5.205357	761.5418	1061.032	16.29675	2.09782
$\varepsilon6$	1.892089	3.638863	165.4363	295.3714	2.976471	2.064682

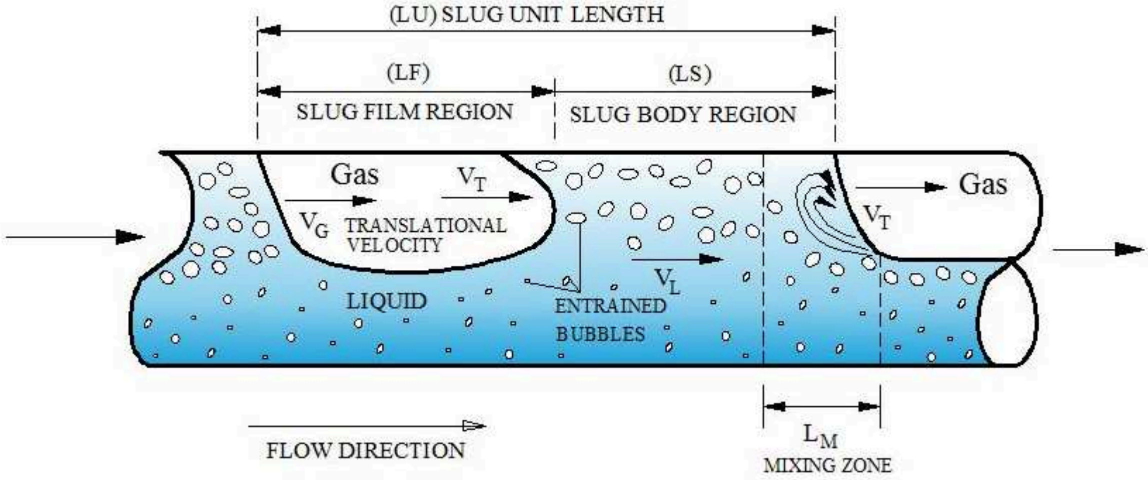


Figure 1: Slug Flow Geometry (Baba, 2016)

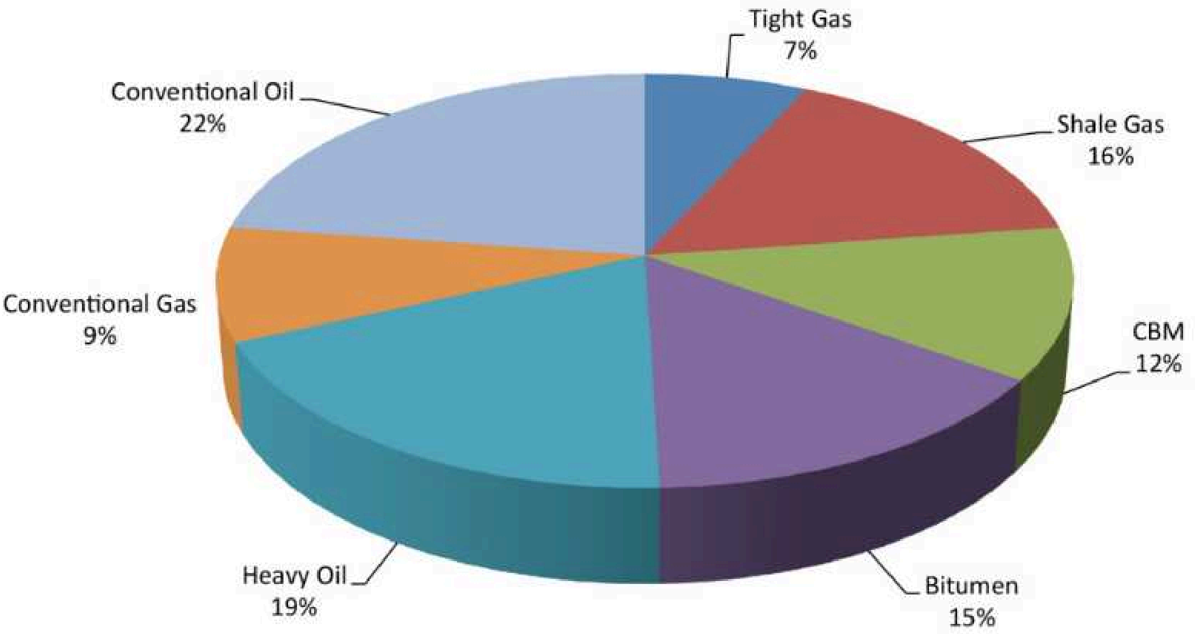
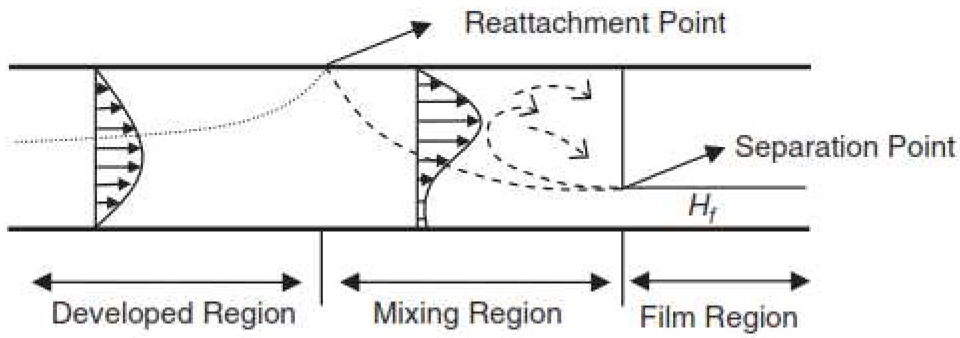
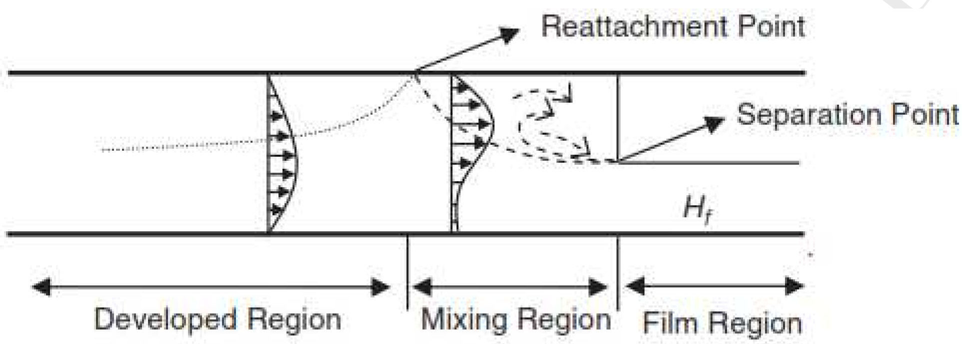


Figure 2: Global oil reserves -conventional versus unconventional resources (Prestine, 2016)



(a)



(b)

Figure 3: (a) Physical model minimum slug length in light oil, (Dukler and Hubbard, 1975) (b) physical model minimum slug length in high viscosity oil, (Al-safran et al., 2013)

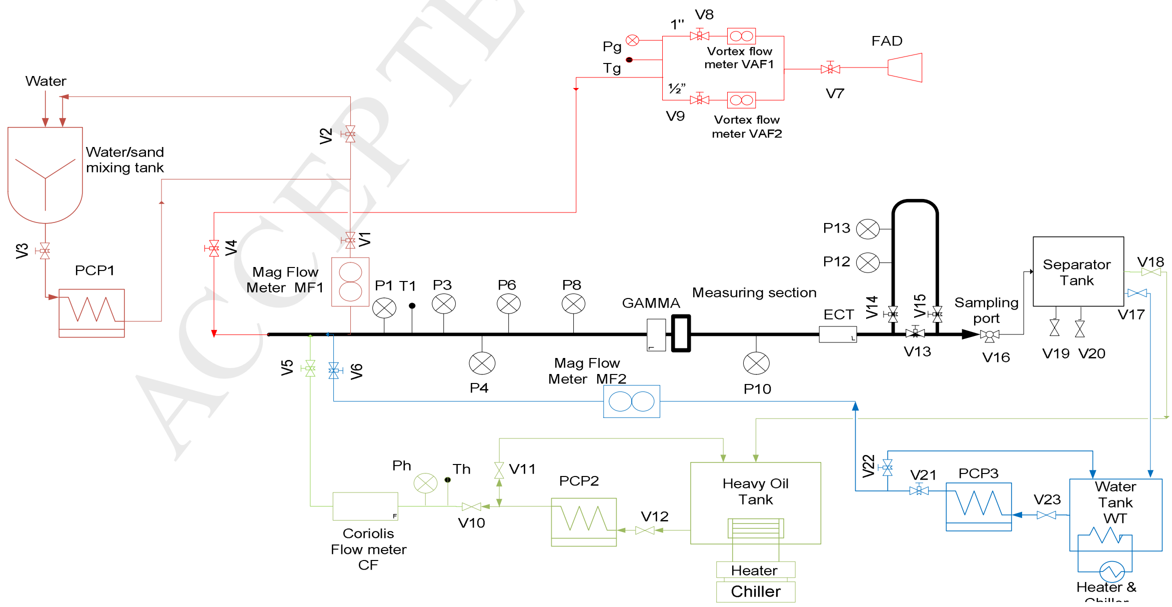


Figure 4: Schematic of experimental test facility.

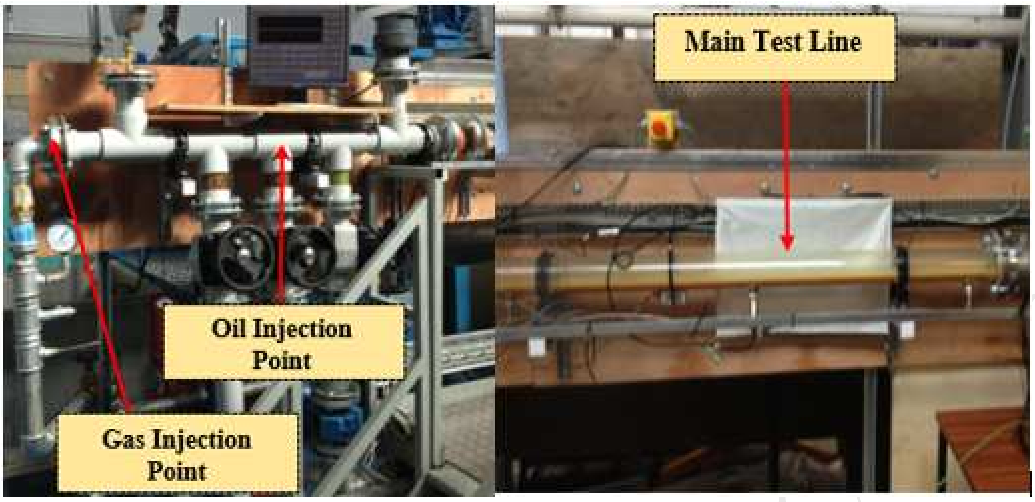


Figure 5: Pictorial view of test facility injection point.

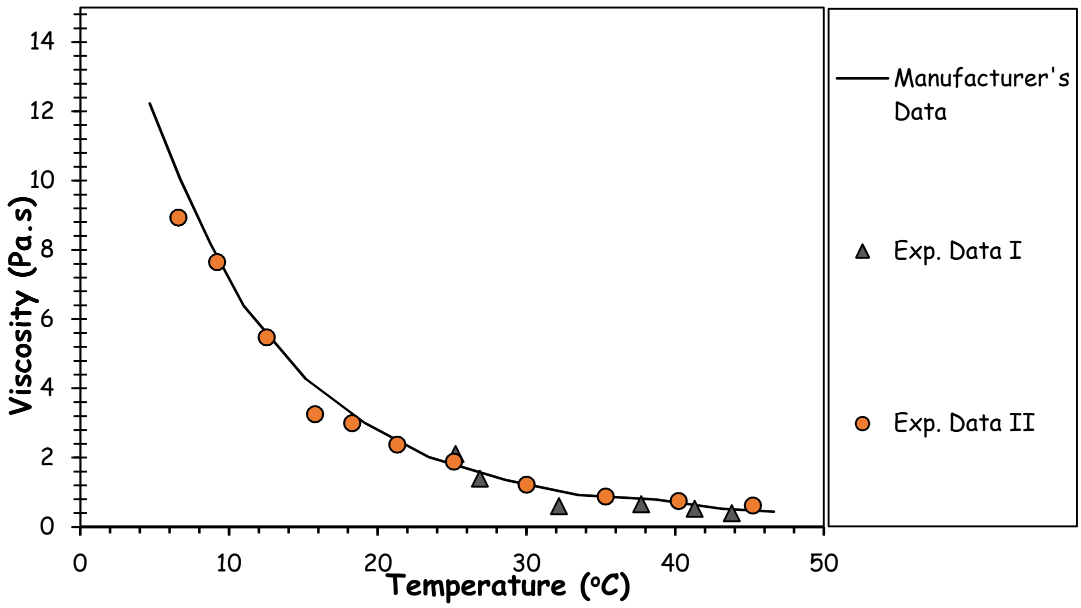


Figure 6: Comparison of measured viscosity and manufacturer's data

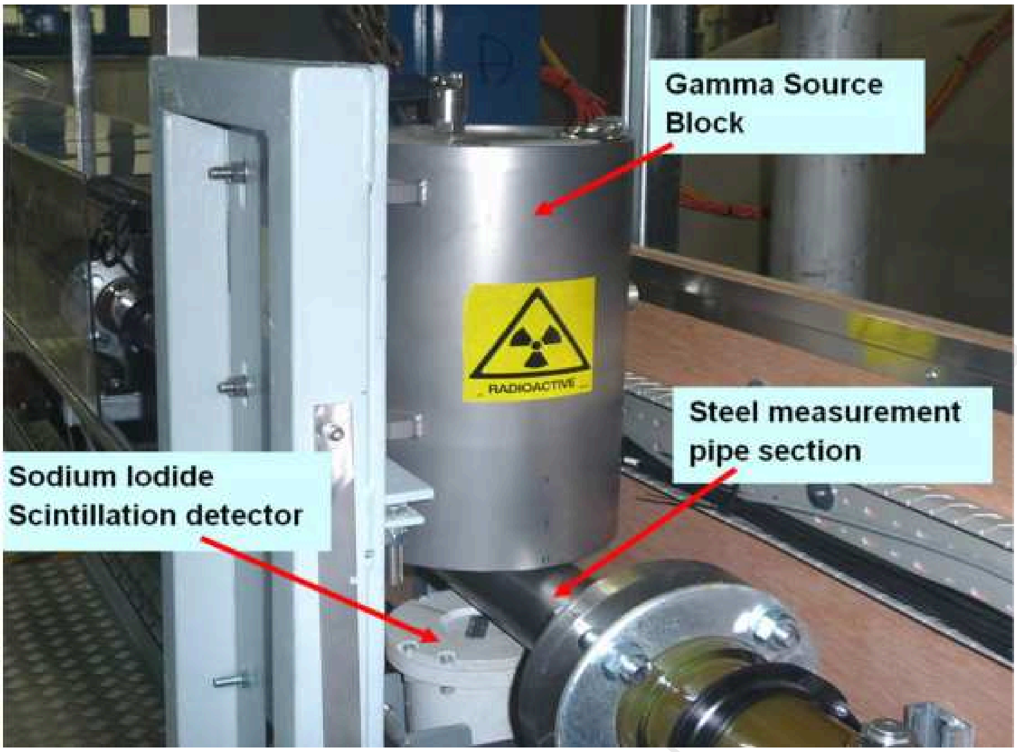


Figure 7: Pictorial representation of gamma ray densitometer used as instrumentation

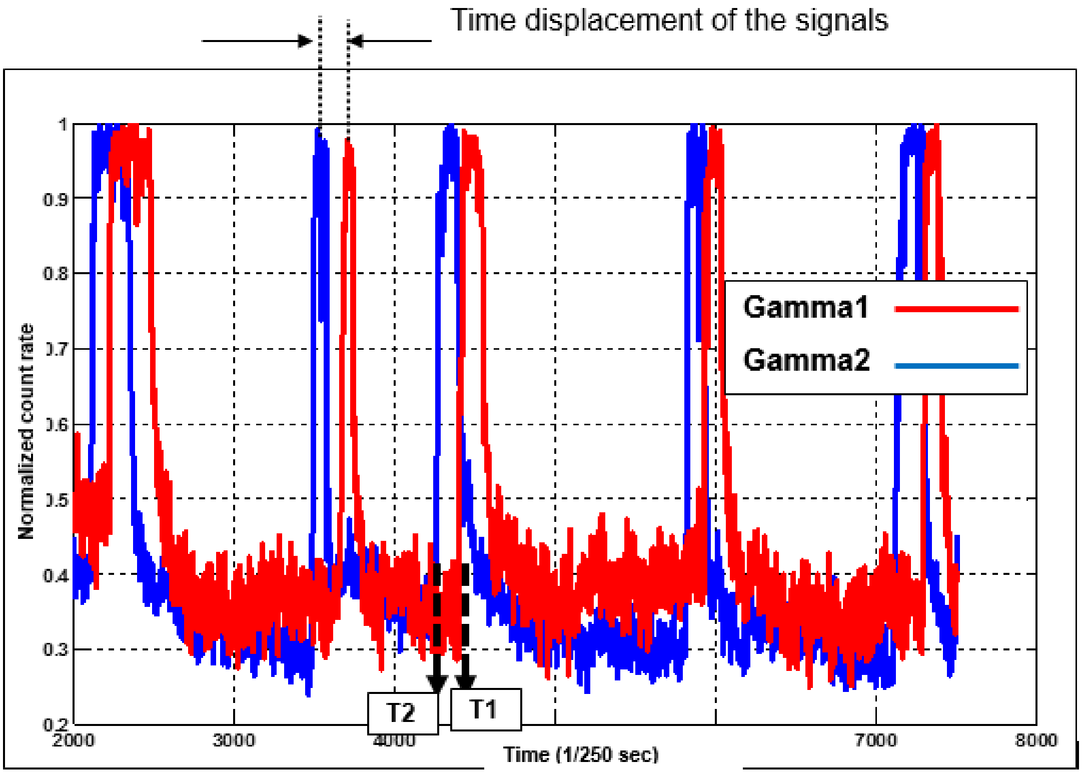


Figure 8: A typical gamma densitometer time series liquid holdup plot for dual Gamma Sensor

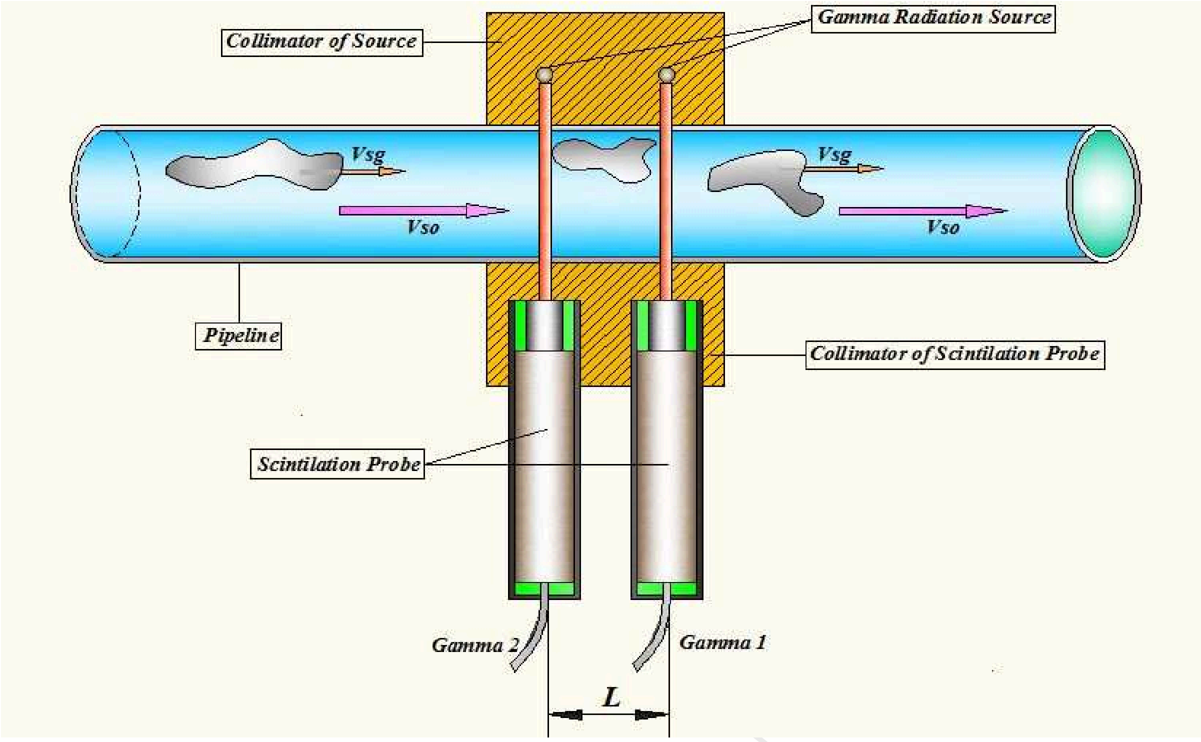


Figure 9: Diagrammatic representation of the Gamma Source installed on the test facility.

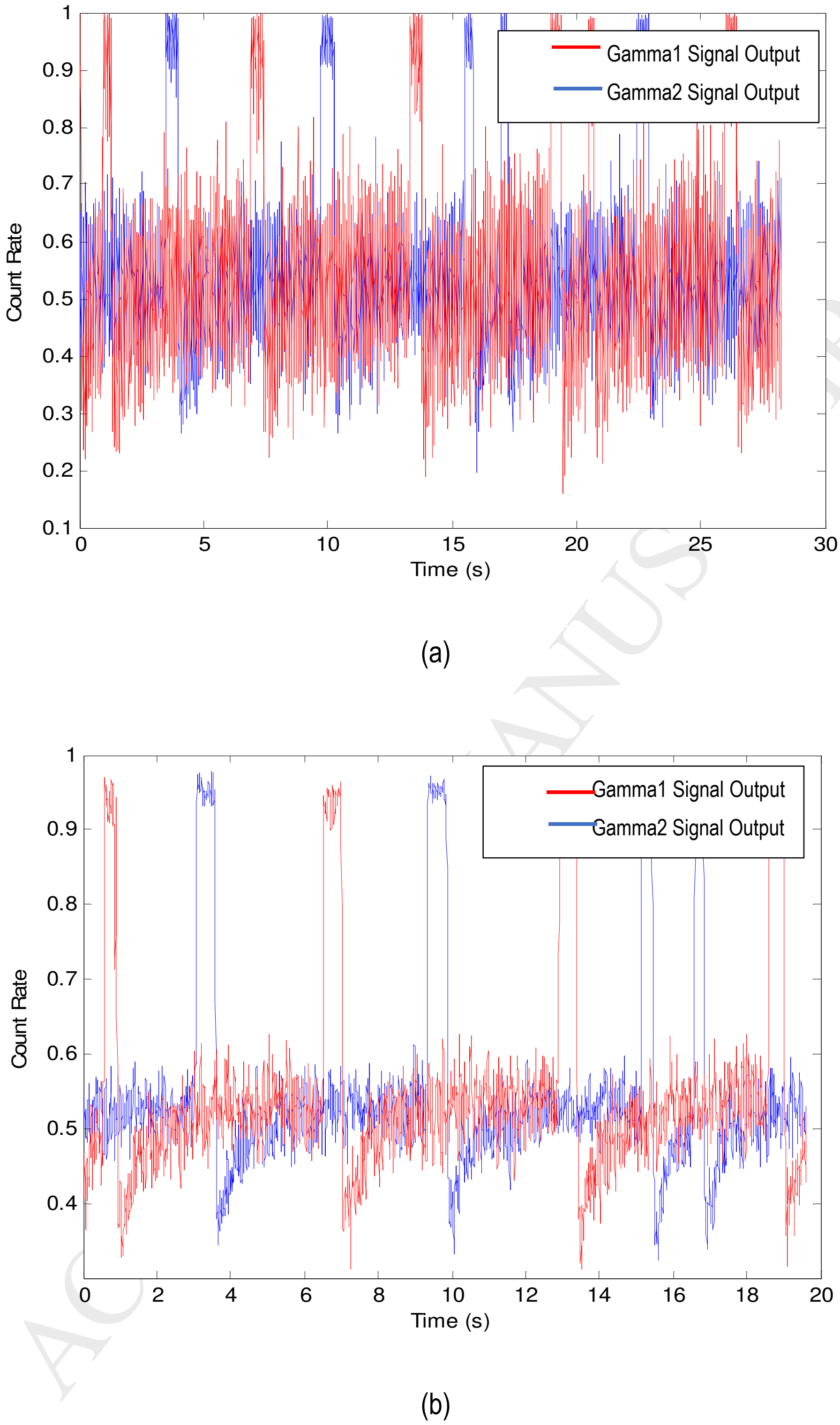


Figure10: (a) Raw signal output from gamma photon counts. (b) Sample of a filtered signal output.

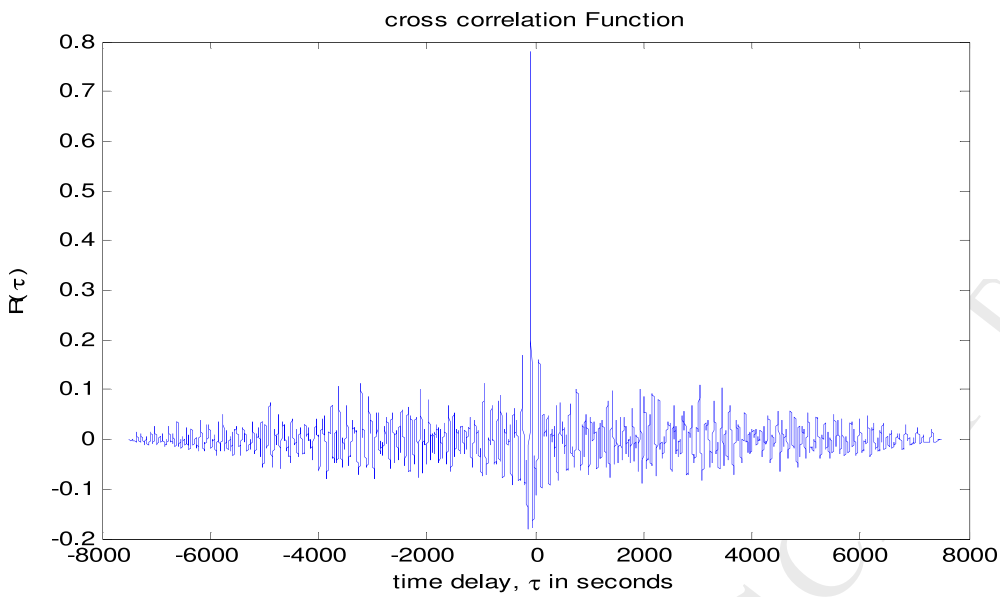
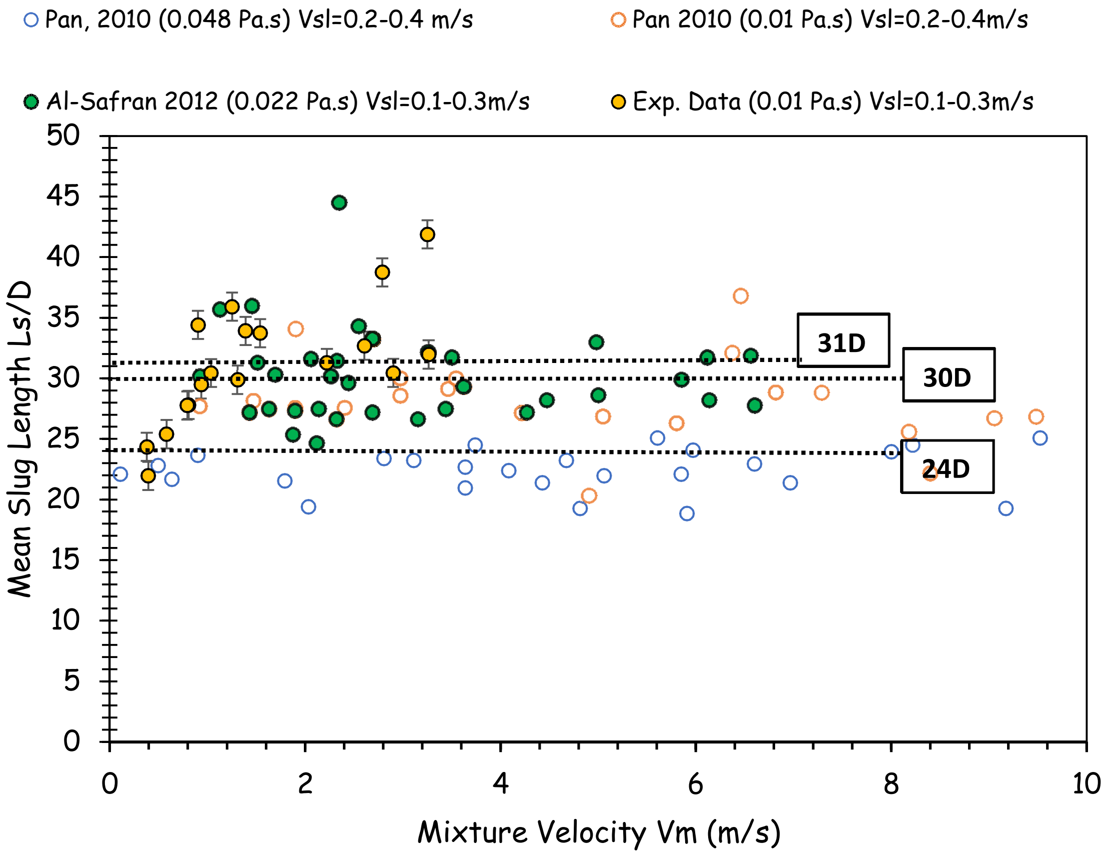
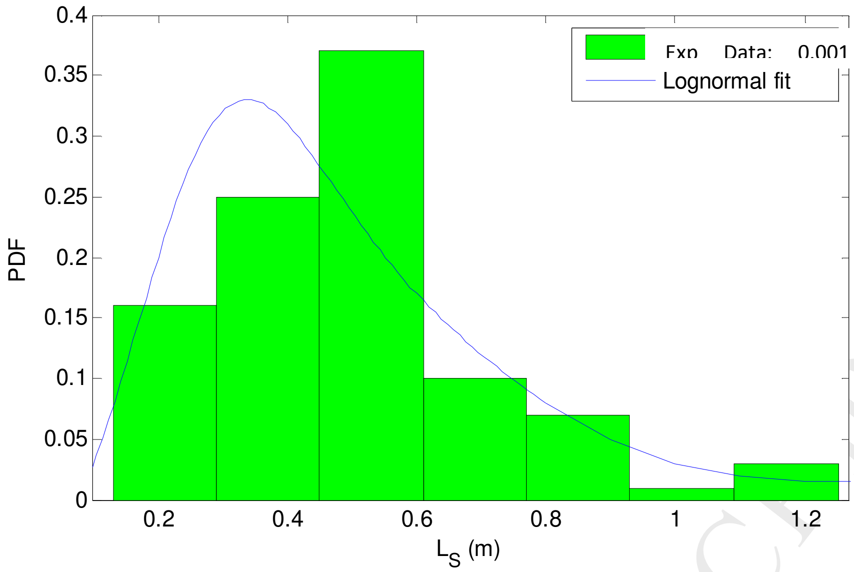


Figure 11: Cross-Correlation results between Gamma 1 and Gamma 2.

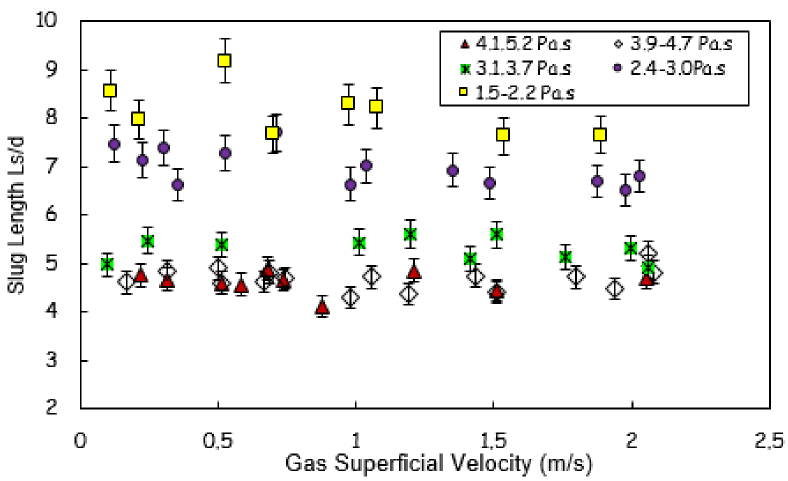


(a)

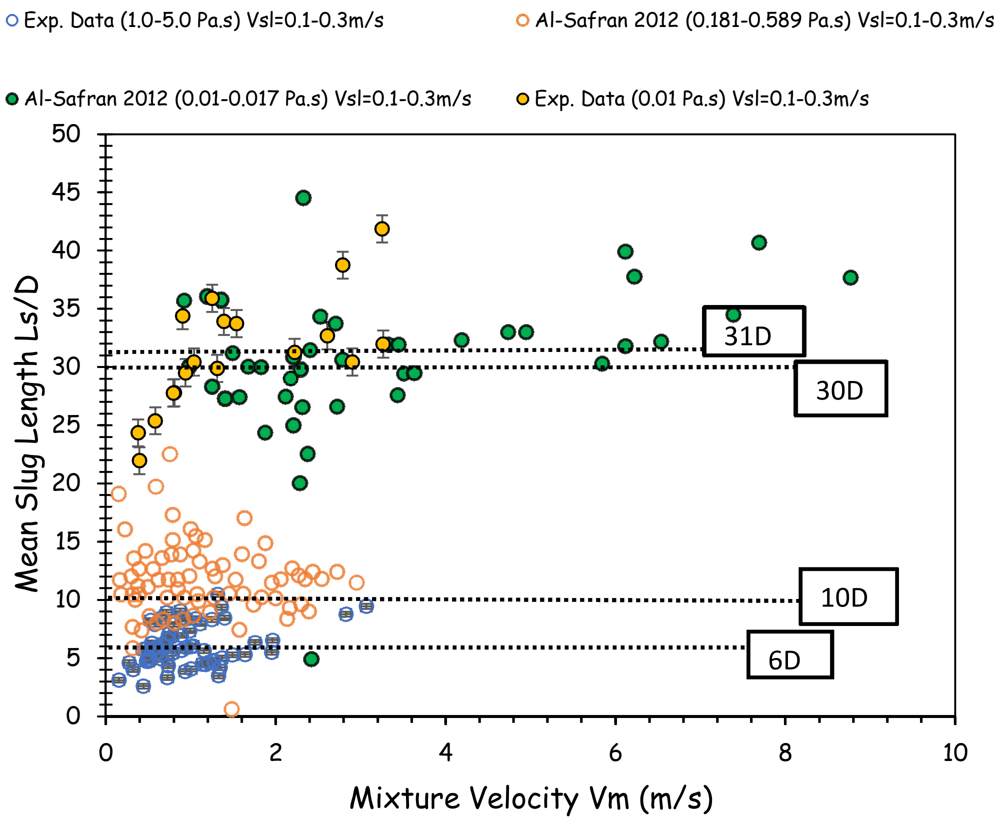


(b)

Figure 12: (a) Measured slug length as a function of mixture velocity (b) Slug length distribution and log-normal fit for flow conditions investigated (Vsg=0.3-7m/s and Vsl=0.2-0.4m/s)



(a)



(b)

Figure 13: (a) Measured slug length versus superficial gas velocity for different superficial liquid velocity Vsl=0.06-0.3m/s. (b) Mean Slug Length as a Function of Mixture Velocity. Error bars were calculated from the uncertainty equation (i.e. Eq. 12) given in Appendix.

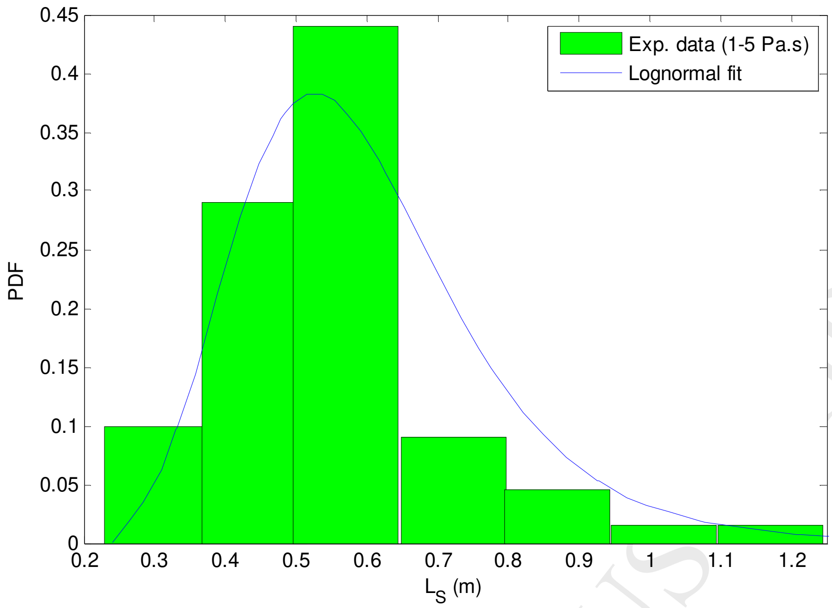


Figure 14: Comparison of experimental result for slug length and Log-Normal distribution.

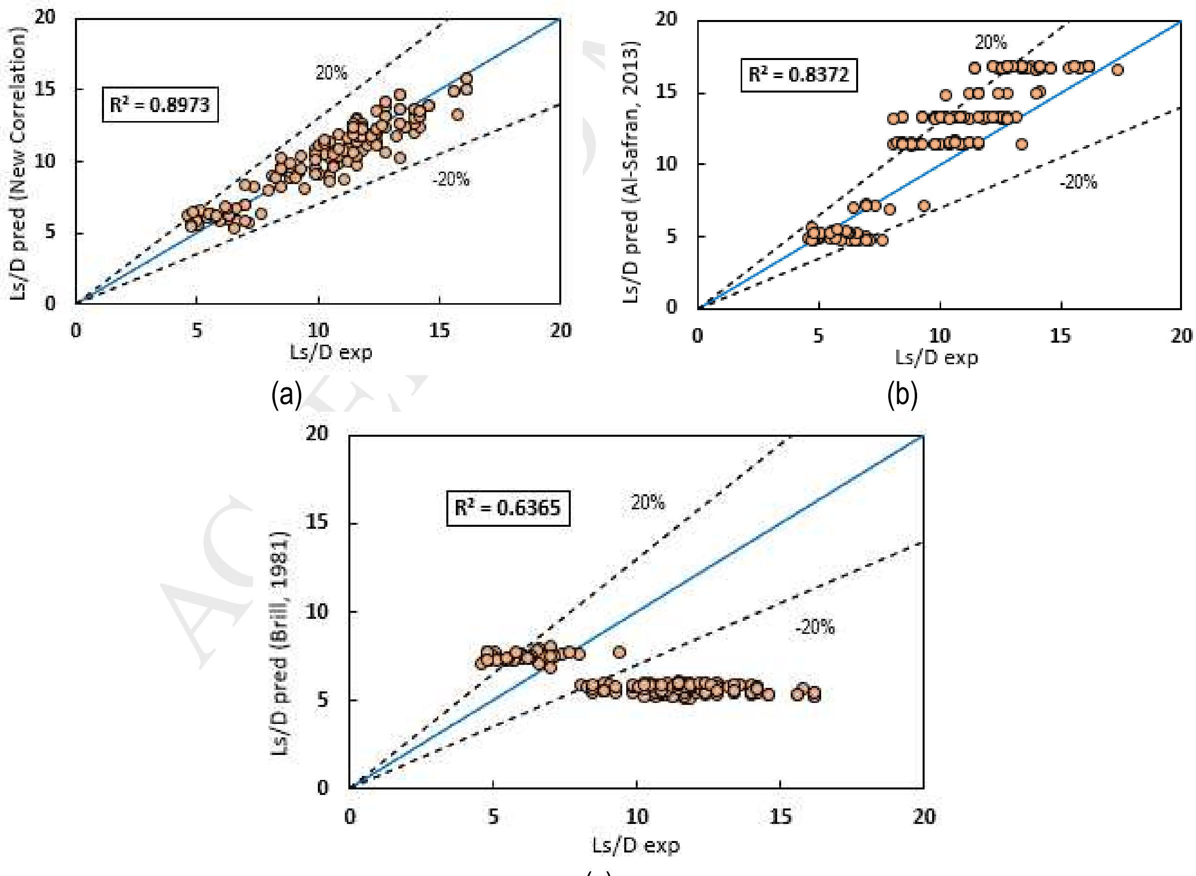


Figure 15: Cross-plot of predictive model predictions for best performing correlations against experimental measurement (a) Current (b) Al Safran (2013) (c) Brill (1981)

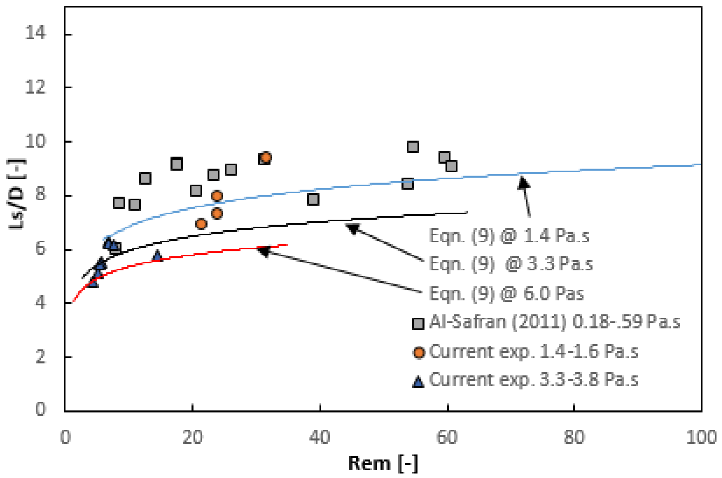


Figure 16: Use of Al-Safran (2013) and current experimental data concerned with oil viscosities ranging from 0.18–6.00 Pa.s to validate Eqn. (9)

Highlights

- High viscosity Liquid-Gas–liquid two-phase flow experiments were conducted in a large diameter horizontal pipe.
- Unique measurements of slug flow features using fast sampling Gamma Densitometer
- Oil viscosity far higher than those found in the literature was used owing to its increasing relevance to the industry.
- Performance evaluation of existing prediction models was carried out against present data
- A new correlation for slug length in high viscosity liquid proposed

2018-02-08

Slug length for high viscosity oil-gas flow in horizontal pipes: experiments and prediction

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